BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B69 12094

SUBJECT: Site Dependent Redesignation and Manual Maneuvering Delta-V Requirements - Case 310

DATE: December 31, 1969

FROM: K. P. Klaasen

ABSTRACT

The redesignation plus manual maneuvering delta-V requirement has been calculated for a 99% probability of landing safely inside of a given circular target area at nine candidate lunar landing sites. This delta-V requirement was then used to make estimates of the site dependent LM payload capability. The delta-V requirement was found to be strongly dependent on the guidance and navigation accuracy. For 3σ automatic landing error ellipses with semi-axes up to about 5,000 ft., all of the candidate sites have available a LM payload capability of at least 800 lb. For 3σ ellipses with semi-axes up to 7,500 ft., a minimum of about 400 lbs. of LM payload capability is available at all sites except Censorinus on an H mission and Rima Bode and Tycho on a J mission. The LM payload capability was calculated using the Apollo 11 redesignation plus descent from 500 ft. delta-V budget and the H and J mission payload capabilities as presented by MSC at the October 30, 1969 Apollo Site Selection Board meeting as a baseline.

During the early portion of the visibility phase of lunar module (LM) descent, delta-V is used to refine targeting by means of redesignations using the landing point designator (LPD). At altitudes below 500 ft. in the LM descent, hazardous landing areas within the target circle are avoided using manual maneuvering. As the radius of the target area increases, the redesignation delta-V requirement decreases while the manual maneuvering requirement increases. The sum of redesignation plus manual maneuvering delta-V becomes a minimum for some particular target area. The size and location of the target may be adjusted to achieve this minimum as long as the desired science return can be realized from any point within the target area. The LM payload estimates were based on the delta-V required to land in the optimum circular target area at each site.

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MEMORANDUM FOR FILE

INTRODUCTION

Estimates of the site specific lunar module (LM) science payload capability are a necessary input to the site selection and mission planning process for the H and J series of lunar landing missions. The site dependency of this payload is due in part to the variation in the LM descent propellant required to land safely in the different types of lunar terrain at each site. The rougher the terrain, the greater the propellant required for redesignation and manual maneuvering during the visibility phase of the descent in order to land safely within a target area from which the desired science return may be achieved. And the more descent propellant required, the less LM payload is available for science. Thus, the site dependent redesignation and manual maneuvering delta-V requirements will help determine what science payload can be landed at a site.

LM DESCENT LANDING PROCEDURE

For each site an acceptable circular area must be determined to which the LM should be targeted. The size and location of this target circle is determined by the science return which can be achieved from a landing within the circle and by the amount of acceptably smooth landing area within the circle. The redesignation and manual maneuvering delta-V is used to make a successful landing inside of this circle.

The characteristics of the LM descent profile shown in Figure 1, the landing point designator (LPD), and the LM manual maneuvering capability cause the procedure for landing site selection during the visibility phase to fall logically into three parts. First, between altitudes of 5,000 ft. and 500 ft., the LPD is used to make gross landing point redesignations in order to correct for guidance and navigation errors and to insure a landing somewhere within the target circle. These redesignations essentially represent a targeting maneuver. Second, between 500 ft. and 100 ft., the LM is maneuvered manually to an acceptably smooth landing site within the target circle. This maneuver is essentially one of hazard avoidance. Third, the vertical descent from 100 ft. to the selected smooth landing point should require a fixed amount of delta-V.

This analysis of LM landing procedures is based on the assumption that the landing area location can be determined visually through the LM window at altitudes up to 5,000 ft., and that hazardous landing areas can be recognized between altitudes of 100 ft. and 500 ft. Proof that such an assumption is valid will depend on the results of future lunar landing missions. Its validity also depends somewhat on the characteristics of the lunar surface around a given site and on the presence of good landmarks.

IMPROVED TARGETING USING THE LPD

Given the LM automatic landing error ellipse and descent trajectory, the probability of landing in a circle of radius Δ using landing point redesignation can be determined for various redesignation strategies and delta-V budgets.[1,2] The pre-mission initial aim point should be biased properly so as to maximize the probability of landing in the target circle in any given case. It was shown in Reference 3 that, although LPD errors tend to reduce this probability, the effects of such errors can be nearly eliminated by using a strategy which involves multiple redesignations. Such a strategy will yield a probability of success only slightly less than that which would result from an errorless redesignation for any given delta-V budget. It was also shown that the probability of success is maximized by redesignating at the greatest possible altitude, in this case 5,000 ft. Thus, the actual redesignation delta-V required to land in a given circle is approximated closely by that required if it is assumed that a single, exact redesignation is made at 5,000 ft. Although redesignations to the left and downrange of the designated landing site are preferred because of landing site visibility limitations, Reference 2 demonstrated the significant delta-V savings which can be realized by allowing uprange and right redesignations to be made without violating the landing site visibility limitation. Therefore, in this analysis, the redesignation delta-V required to land within a circle of radius Δ with a given probability of success was calculated assuming a single, exact redesignation at 5,000 ft. altitude allowing left, downrange, 10° right, and 4,000 ft. uprange redesignation capability. The resulting delta-V costs are plotted in Figure 2 assuming the Apollo 12 descent trajectory, 1σ automatic landing error circles of radius 1640 ft. (1/2 kilometer) and 2500 ft., and a 99% probability of landing in the target circle.

HAZARD AVOIDANCE USING MANUAL MANEUVERING

As the LM passes below 500 ft. altitude, it is assumed that there is a 99% chance that the eventual landing point will be somewhere in the target circle of radius Δ without further maneuvering. This 99% probability has been assured either by initial targeting and small guidance and navigation dispersions or by redesignating into the circle. Now to insure a safe landing within the target, enough delta-V must be available to avoid the largest unacceptable landing area within the circle using manual maneuvering. For any site, the dimension of the largest reject area to be avoided is determined by the terrain characteristics at the site and the radius and location of the target circle. The Mapping Sciences Laboratory at MSC has examined the high resolution photography of nine candidate landing sites and has indicated the reject areas within a 1 km radius circle at each site.[4] These circles are located such that a landing anywhere within the circle will allow for adequate science return. Thus, the target circle of radius Δ should be located such that it encloses as much acceptable landing area inside of the 1 km science circle as possible. Area outside of the science circle is considered to be reject area.

The time required to fly a distance D over a reject area is given by

$$t = \frac{D}{V}$$

where V is the average horizontal velocity of the LM during the over fly maneuver. The delta-V required by the LM during this maneuver is 5.3 ft/sec/sec. Thus,

$$\begin{aligned} \Delta V_{manual} &= 5.3(t)\,\text{ft/sec} \\ &= 5.3\left(\frac{D}{V}\right)\text{ft/sec} \end{aligned}$$

The horizontal forward velocity of the LM at 500 ft. altitude is about 80 ft/sec. A reasonable estimate of the average horizontal velocity during a hazard avoidance maneuver is about 50 to 60 ft/sec. By letting V = 53 ft/sec we have the simple relationship that

$$\Delta V_{manual} = \left(\frac{D}{10}\right)\ \text{ft/sec}$$

A plot of the manual maneuvering capability footprint for Apollo 12,given in Figure 3, shows the footprint to be approximately a semi-circle downrange of the designated landing site.[5] Such a footprint indicates a fairly constant average horizontal velocity for a maneuver in any direction except uprange. Since maneuvers to a point uprange of the designated landing point are very limited in range and have an average velocity much less than 53 ft/sec, such maneuvers should be avoided, and the target circle should be located so that it does not enclose any points downrange of the furthest downrange acceptable landing area inside of the 1 km circle. Thus, for a landing at Tycho, the target circle should enclose only areas uprange of the boundary shown in Figure 4.

In order to find the manual maneuvering delta-V required to land safely inside of the target circle of radius Δ at any particular site, the target circle should be located so that the longest distance D from a point in a reject area within the target circle to an acceptable landing point downrange and/or crossrange of that reject point is a minimum. The delta-V available must be sufficient to fly over the largest distance D within the target circle; however, the location of the target circle can be chosen to minimize this D. Obviously as Δ increases the D associated with that target radius will remain constant or increase. So for larger target areas, larger manual maneuvering delta-V budgets are required at any given site.

TRADEOFF BETWEEN REDESIGNATION AND MANUAL MANEUVERING DELTA-V

The redesignation delta-V requirement decreases for increasing Δ, as shown in Figure 2, while the manual maneuvering delta-V increases with Δ. The sum of redesignation plus manual maneuvering delta-V may reach a minimum value for some optimum Δ. Figures 5a, b and c show the redesignation and the manual maneuvering delta-V and their sum as a function of Δ for each of the nine mapped sites and for 1σ landing error circles of radius 1,640 ft. and 2,500 ft. The manual maneuvering delta-V requirements were determined graphically by properly locating target circles of different sizes on the maps of the landing sites following the method described in the previous section. The distance D and the related delta-V were then determined for each target circle. The delta-V requirements for the various target circles were then plotted and connected by straight lines in Figure 5. Notice that in several cases the minimum of the redesignation plus manual maneuvering delta-V curves is rather flat about the true minimum point. Thus, there exists a range of Δ's about the optimum Δ over which the delta-V requirement is approximately at the minimum value. Figure 6 presents a table summarizing the redesignation plus manual maneuvering delta-V required over the range of Δ's near the optimum value of Δ for each site. Note the strong dependence of the delta-V requirement on the size of the landing error ellipse. Figures 7a and b show the proper size and location of the optimum target circle as determined in Figures 5 and the initial aim point for the case of σ = 1,640 ft. The initial aim point bias was based on the capability of the redesignation delta-V required. The aim point is located approximately a distance of

1/2 [(uprange capability)-(downrange capability)]

downrange and

1/2 [(left capability)-(right capability)]

right of the center of the target circle as presented in Reference 2.

LM PAYLOAD ESTIMATES

An estimate of the available LM payload capability for each site can be obtained from a comparison of the site dependent redesignation plus manual maneuvering delta-V requirements with the delta-V budget for the Apollo 11 mission. For Apollo 11, 60 fps were budgeted for redesignation and 2 minutes time or 636 fps were allowed for the descent from 500 ft. altitude to touchdown. Assuming this redesignation plus descent from 500 ft. delta-V budget, the available LM payload is about 800 lbs. for an H mission and 1,025 lbs. for a J mission.[6] For H and J missions, the delta-V budget for descent from 500 ft. can be determined by allowing 80 sec. for an automatic descent, plus site dependent hazard avoidance time, plus 30 seconds of discretionary time to allow for any contingencies and to enable the safest possible landing to be made. The redesignation requirements are also site dependent. So for an H or J mission site, the redesignation plus descent from 500 ft. delta-V requirement consists of:

redesignation delta-V
+ manual maneuvering delta-V
+ (110 sec.) (5.3 ft/sec^2)

A comparison of this delta-V requirement with the 696 fps budgeted for Apollo 11 will yield a Δ (ΔV) requirement for each site. This Δ (ΔV) can be converted to a change in LM payload above or below the baseline LM payload capability for the given type of mission by using the conversion factor of 3.2 lbs/fps. A table listing the LM payload estimates for each site is given in Figure 8 for landing error circles of σ = 1,640 ft. and σ = 2,500 ft. For σ = 1,640 ft., a minimum of 800 lbs. of payload can be landed at all candidate sites while for σ = 2,500 ft., a minimum of about 400 lbs. can be landed at all sites except Censorinus on an H mission and Rima Bode and Tycho on a J mission. The best estimate 3σ error ellipse for Apollo 12 is 7,000 ft. x 4,500 ft. which is approximately equivalent to a 1σ circle of radius 2,000 ft. Such an ellipse would allow LM payloads somewhere between the values for the two error circles listed in Figure 8.

CONCLUSIONS

The size and location of a circular landing target area for lunar exploration sites are acceptable if the desired science return can be achieved from any landing point within the target circle. During LM descent, landing point redesignations are used to reduce guidance and navigation errors to the target circle, and manually controlled maneuvers are used below 500 ft. to avoid any hazardous landing areas within the target circle. Within the constraint of being able to achieve an adequate science return, the size and location of the target area for each site should be adjusted so as to minimize the amount of redesignation plus manual maneuvering delta-V required to effect a safe landing within the target area with a given probability of success. The delta-V required is very dependent on the guidance and navigation accuracy. Using the Apollo 11 redesignation plus descent from 500 ft. delta-V budget and the H and J mission LM payload capabilities as a baseline, it appears that for 3σ landing ellipses with semi-axes up to about 5,000 ft. a minimum of 800 lbs. of LM payload can be landed in the target with a 99% probability of success at all nine sites for the presently proposed missions. For 3σ ellipses with semi-axes up to 7,500 ft., a minimum of about 400 lbs. can be landed at all sites with the exception of Censorinus on an H mission and Rima Bode and Tycho on a J mission.

K.P. Klaasen

2013-KPK-srb K. P. Klaasen

Attachments:
References
Figures 1 through 8

REFERENCES

1. Klaasen, K. P., "Use of the Landing Point Designator to Land the Lunar Module in a Circular Target Area", Case 310, Bellcomm Memorandum for File, B69 09039, September 16, 1969.

2. Klaasen, K. P., "Effects of Including Uprange and Right Redesignation Capability on Landing the Lunar Module in a Circular Target Area", Case 310, Bellcomm Memorandum for File, B69 12069, December 22, 1969.

3. Klaasen, K. P., "Effects of Landing Point Designator Errors on Landing the Lunar Module in a Circular Target Area", Case 310, Bellcomm Memorandum for File, B69 12012, December 2, 1969.

4. Perrine, C., "Estimated LM Payload Penalties for Precision Landing in Rough Terrain", MSC Memorandum, PD12/M850-69, September 17, 1969.

5. Bennett, F. V., "Presentation on Apollo 12 LM Descent", Apollo Guidance Software Task Force Meeting, October 19, 1969.

6. MSC Presentation to Apollo Site Selection Board, October 30, 1969.

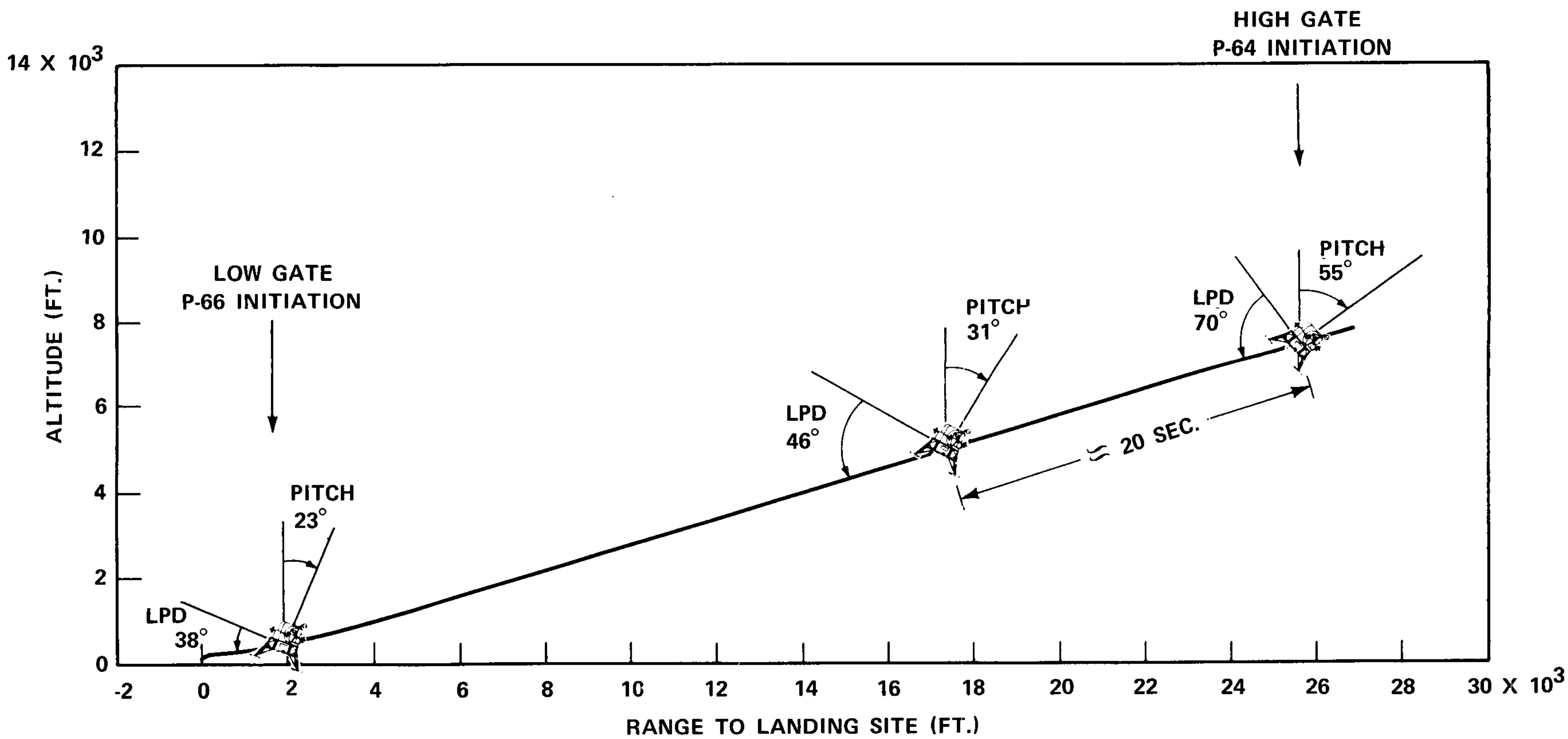

FIGURE 1 – APOLLO 12 NOMINAL LM DESCENT TRAJECTORY

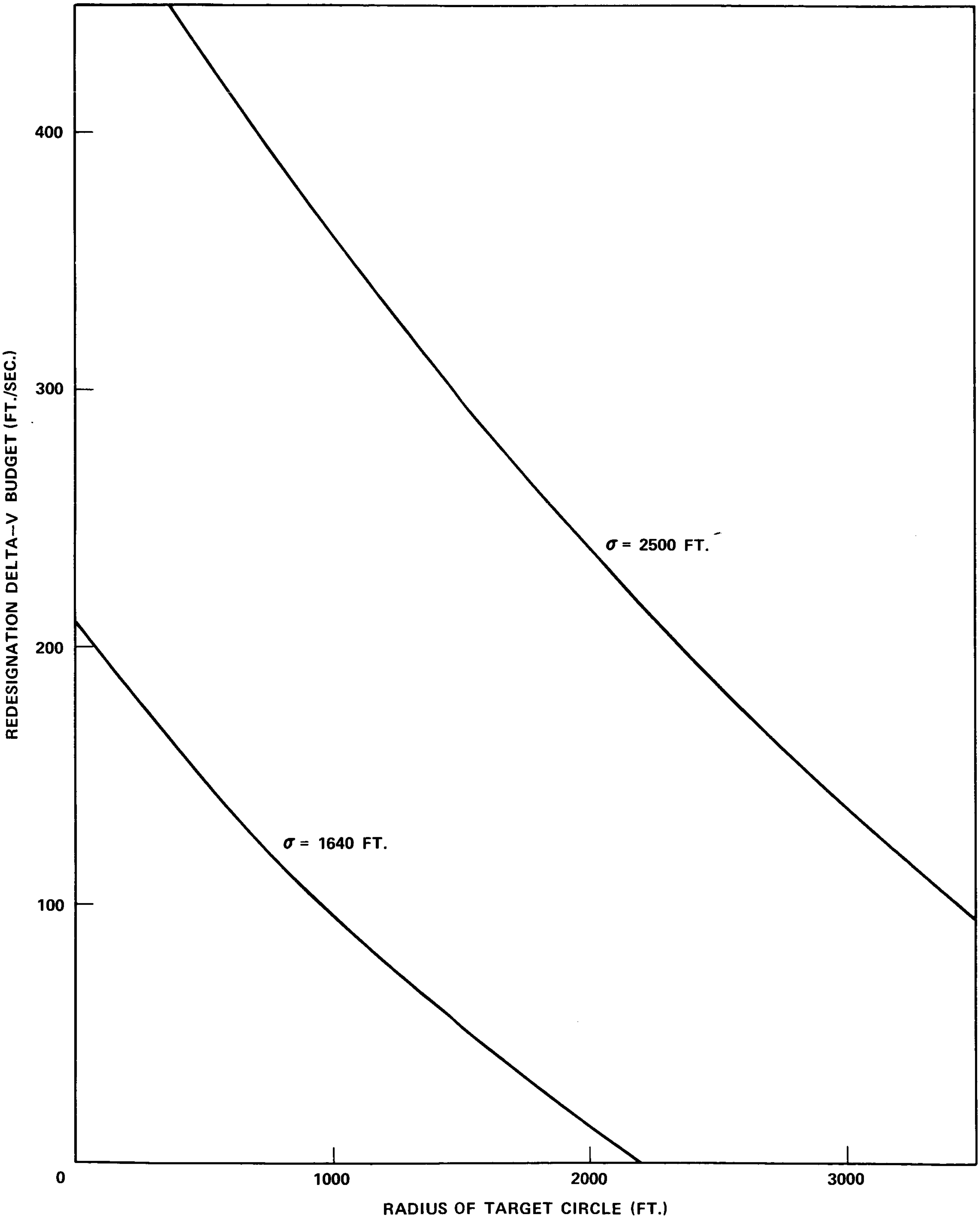

FIGURE 2 – REDESIGNATION DELTA–V COSTS FOR 99% PROBABILITY OF LANDING WITHIN THE TARGET AREA

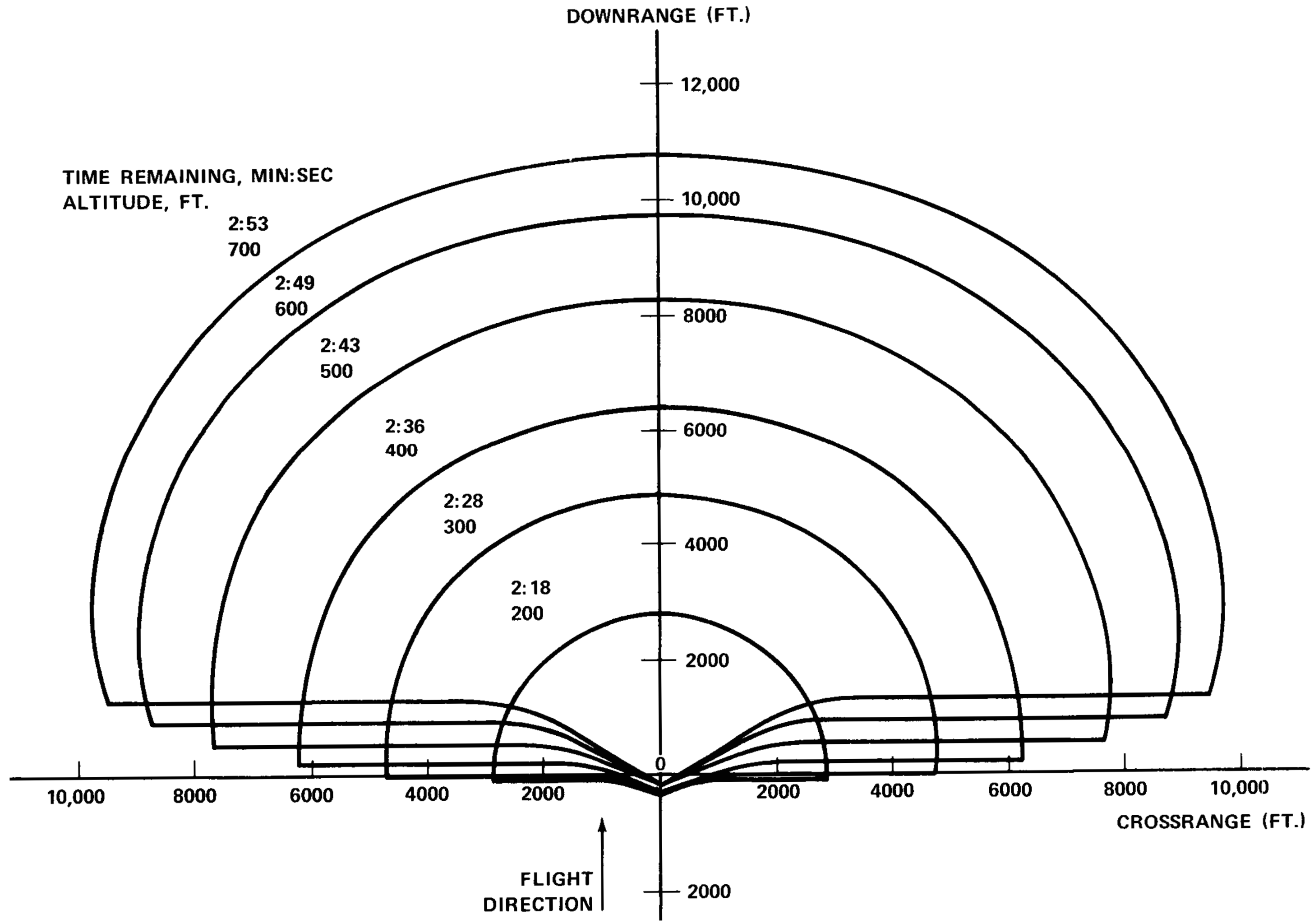

FIGURE 3 – MANUAL MANEUVERING CAPABILITY FOOTPRINT

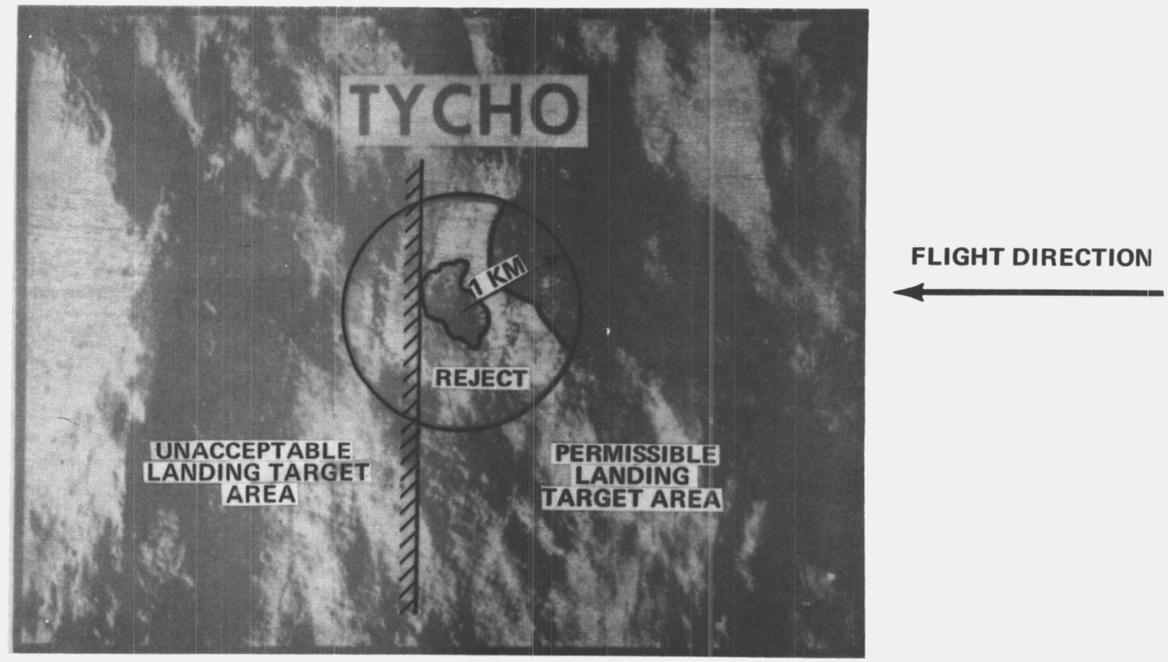

FIGURE 4 - TARGET AREA MUST BE LOCATED UPRANGE OF THE FURTHEST DOWNRANGE ACCEPTABLE LANDING POINT WITHIN THE 1 KM SCIENCE CIRCLE.

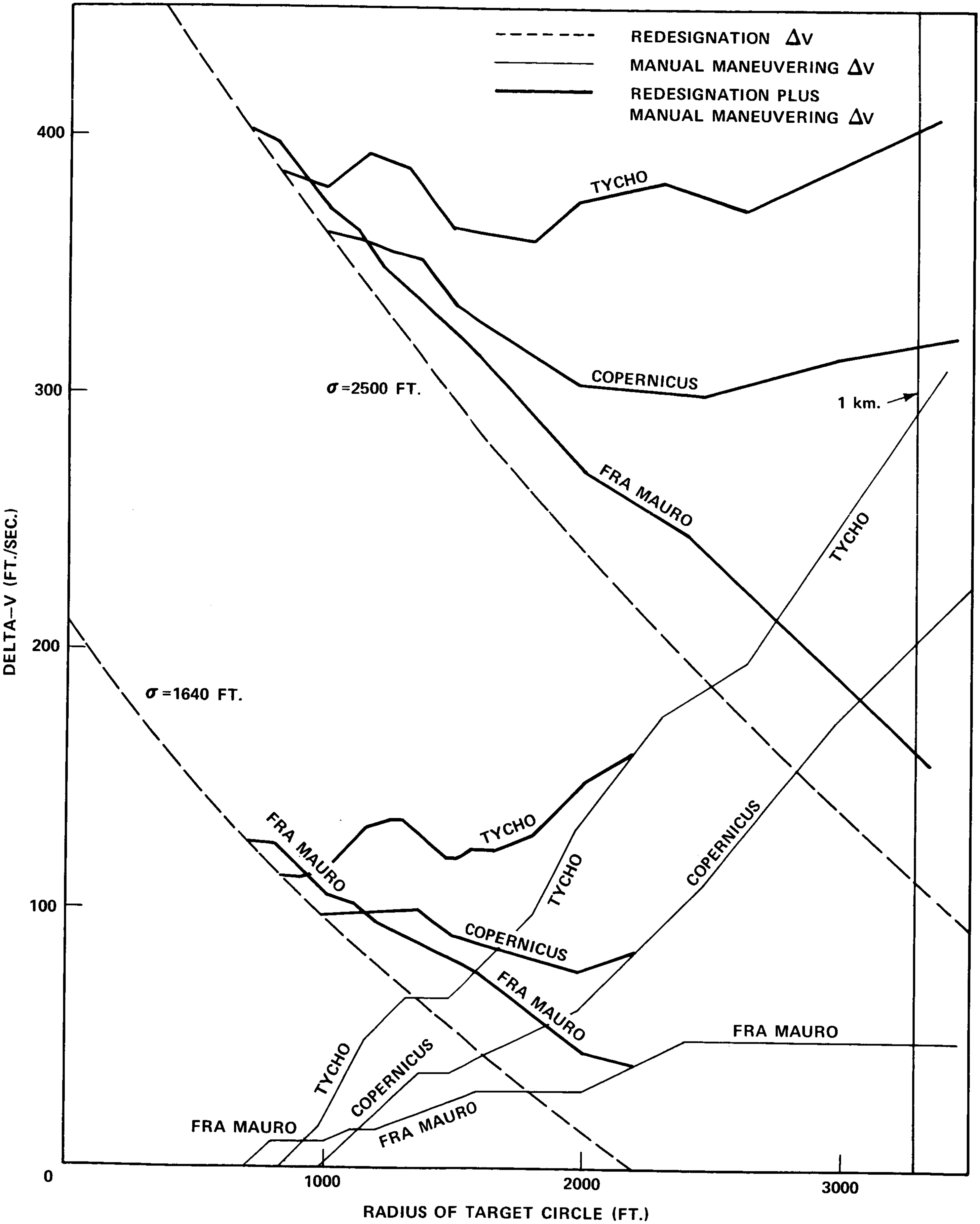

FIGURE 5A – REDESIGNATION AND MANUAL MANEUVERING DELTA–V REQUIREMENTS FOR TYCHO, COPERNICUS, AND FRA MAURO

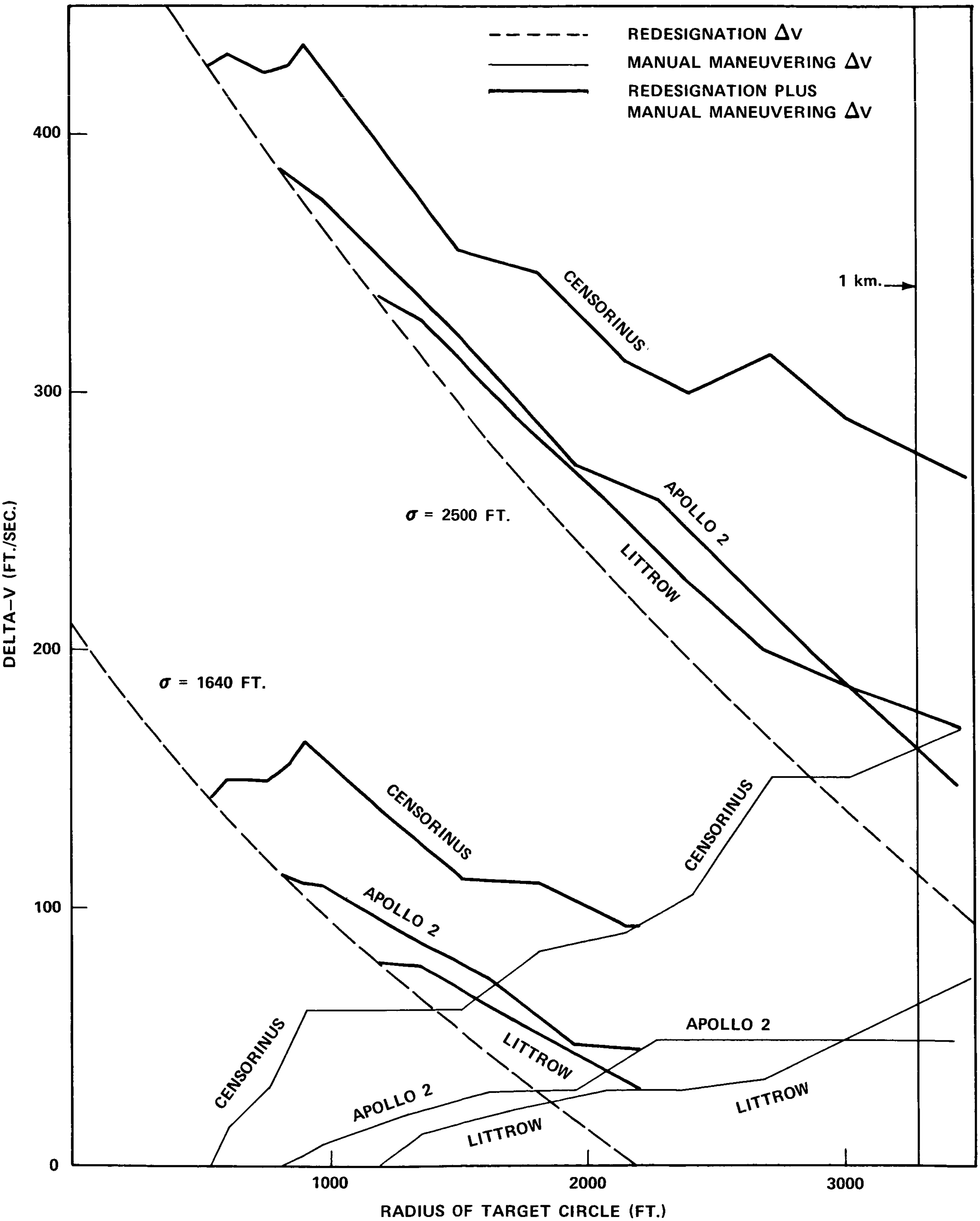

FIGURE 5B – REDESIGNATION AND MANUAL MANEUVERING DELTA–V REQUIREMENTS FOR CENSORINUS, APOLLO 2, AND LITTROW

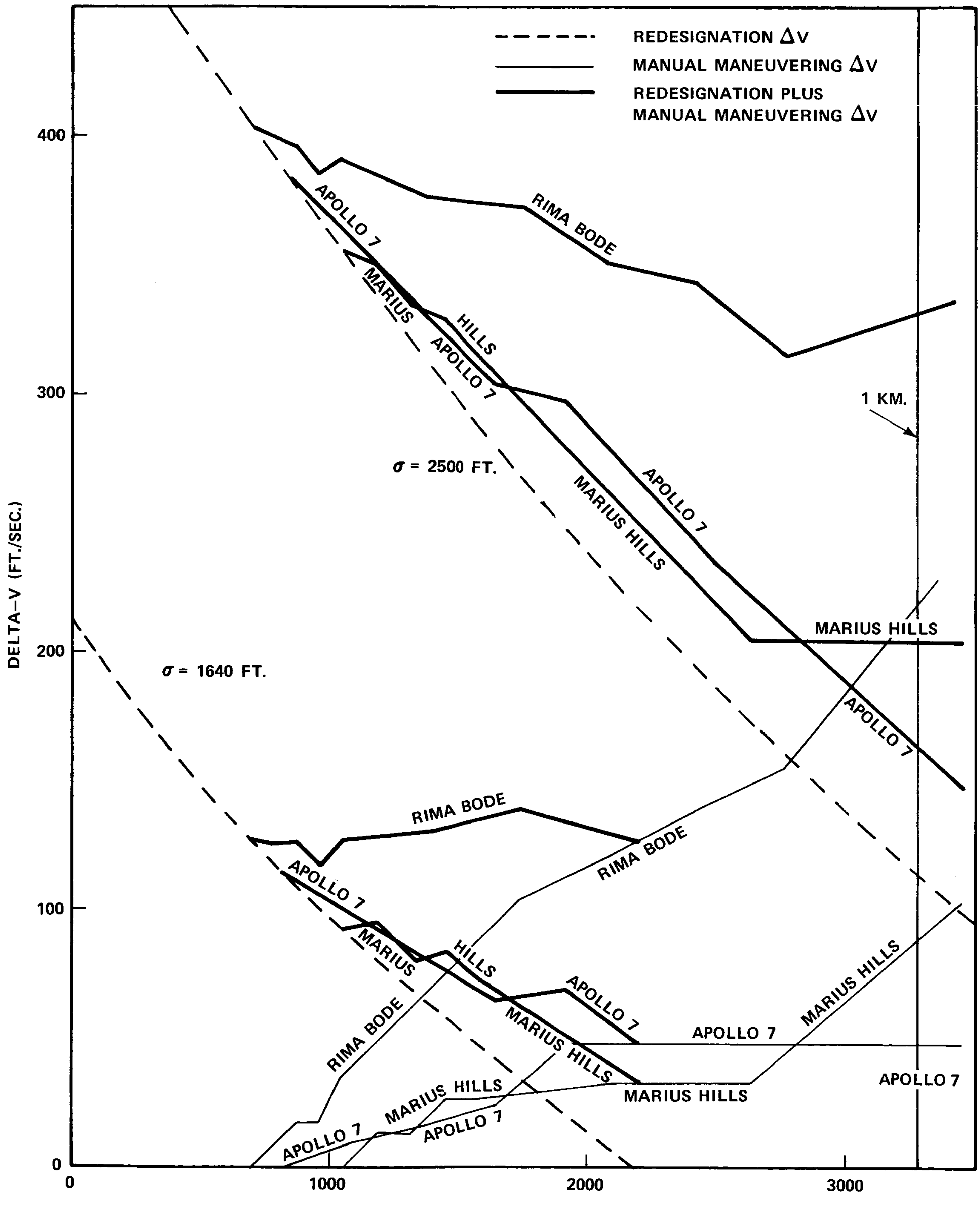

FIGURE 5C – REDESIGNATION AND MANUAL MANEUVERING DELTA–V REQUIREMENTS FOR RIMA BODE, MARIUS HILLS, AND APOLLO 7

SITE	ONE SIGMA AUTOMATIC LANDING ERROR CIRCLE RADIUS			
	σ = 1640 FT		σ = 2500 FT	
	DELTA-V (FPS)	RANGE OF OPTIMUM TARGET AREA RADII (FT)	DELTA-V (FPS)	RANGE OF OPTIMUM TARGET AREA RADII (FT)
APOLLO 2	50	1900 TO 3300	180	3100 TO 3300
LITTROW	40	2000 TO 2800	190	2900 TO 3300
APOLLO 7	50	2200 TO 3300	180	3100 TO 3300
MARIUS HILLS	40	2100 TO 2700	210	2600 TO 3300
FRA MAURO	50	2000 TO 3300	200	2900 TO 3300
CENSORINUS	110	1500 TO 2400	290	3000 TO 3300
COPERNICUS	100	1000 TO 2300	310	1900 TO 2800
RIMA BODE	140	600 TO 2400	330	2600 TO 3200
TYCHO	140	600 TO 2400	400	700 TO 3200

FIGURE 6 – REDESIGNATION PLUS MANUAL MANEUVERING DELTA-V REQUIREMENTS

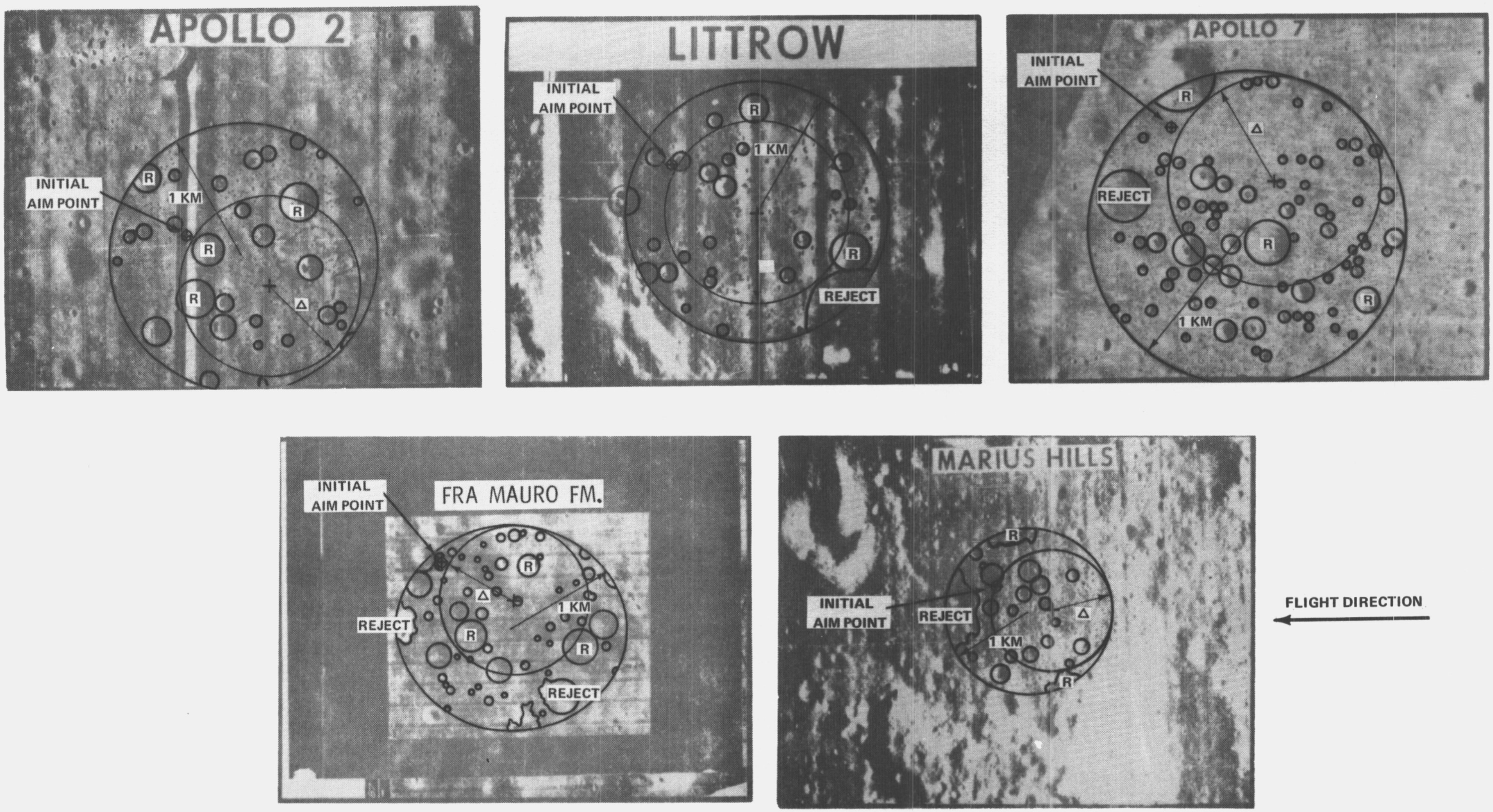

FIGURE 7A - LOCATION AND SIZE OF OPTIMUM TARGET CIRCLE AND INITIAL AIM POINT FOR AUTOMATIC LANDING ERROR CIRCLE WITH σ = 1640 FT.

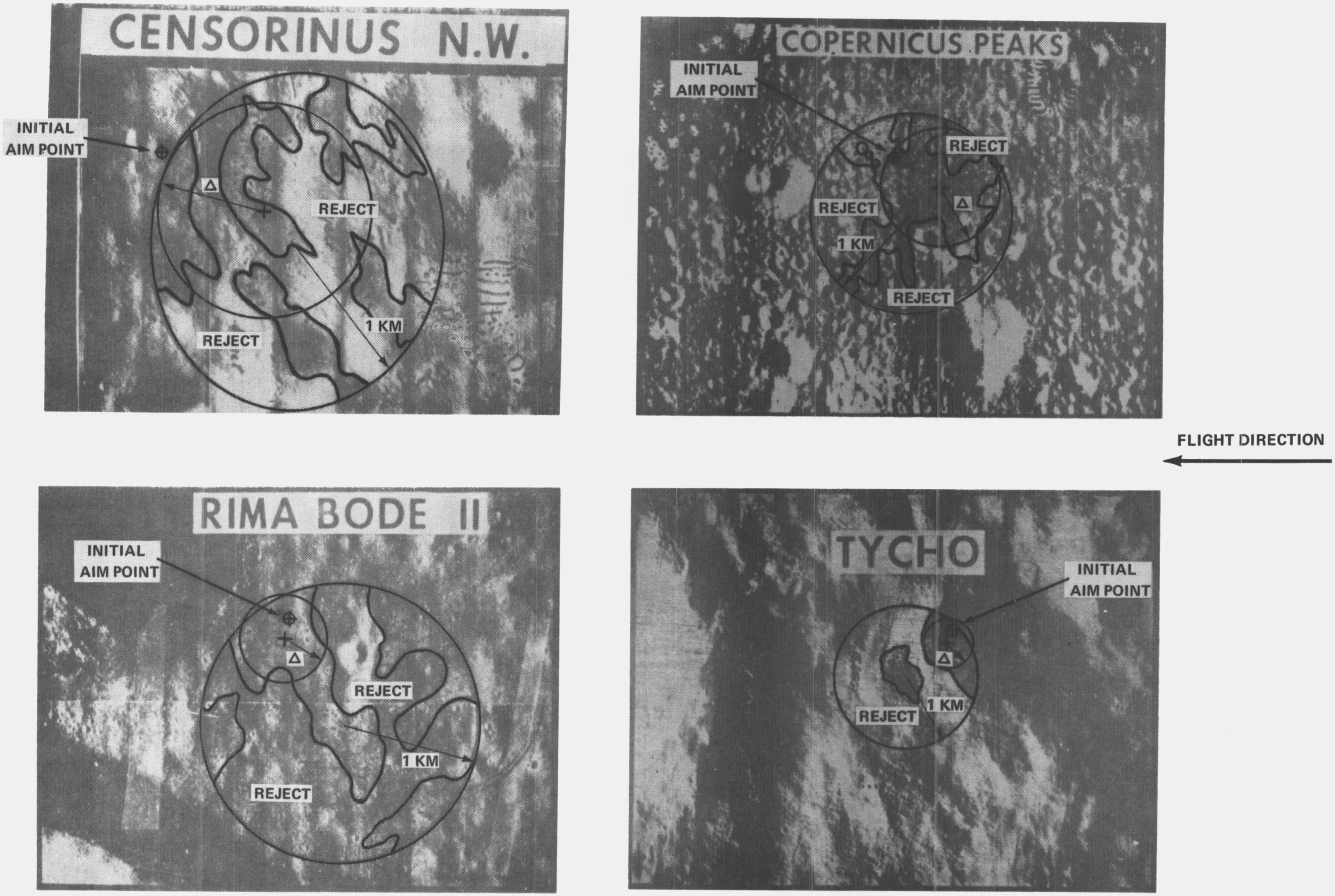

FIGURE 7B - LOCATION AND SIZE OF OPTIMUM TARGET CIRCLE AND INTIAL AIM POINT FOR AUTOMATIC LANDING ERROR CIRCLE WITH σ = 1640 FT.

SITE	TYPE OF MISSION	ONE SIGMA AUTOMATIC LANDING ERROR CIRCLE RADIUS					
		σ = 1640 FT			σ = 2500 FT		
		$\Delta(\Delta V)$ OVER APOLLO II BUDGET (FPS)	Δ LM PAYLOAD (LB)	AVAILABLE LM PAYLOAD (LB)	$\Delta(\Delta V)$ OVER APOLLO II BUDGET (FPS)	Δ LM PAYLOAD (LB)	AVAILABLE LM PAYLOAD (LB)
APOLLO 2	H	–63	+202	1002	+67	–213	587
LITTROW	H	–73	+234	1034	+77	–246	554
APOLLO 7	H	–63	+202	1002	+67	–213	587
FRA MAURO	H	–63	+202	1002	+87	–278	522
CENSORINUS	H	–3	+10	810	+177	–566	234
CENSORINUS	J	–3	+10	1035	+177	–566	459
MARIUS HILLS	J	–73	+234	1259	+97	–310	715
COPERNICUS	J	–13	+42	1067	+197	–631	394
RIMA BODE	J	+27	–86	939	+217	–695	330
TYCHO	J	+27	–86	939	+287	–919	106

FIGURE 8 – SITE DEPENDENT LM PAYLOAD ESTIMATES

BELLCOMM, INC.

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From: K. P. Klaasen

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